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Global Energetic Neutral Atom (ENA) Measurements and Their Association With the *Dst* Index.

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Abstract.
We present a Global Energetic Neutral Index (GENI) derived from POLAR/CEPPAD energetic neutral atom (ENA) measurements. This index tracks the *Dst* index remarkably well over a wide range of conditions, including the quiet time ring current as well as during all phases of moderate geomagnetic storms. The first experimental association between ENAs and *Dst* was reported by Roelof et al. [1985] using several ENA observations from IMP 7/8 and ISEE 1. They derived theoretically and demonstrated experimentally a relationship between ENA fluxes and the rate of ring current recovery as measured by the *Dst* index. More recently, Lui et al. [1996] observed ENA time evolution associated with a large geomagnetic storm using GEOTAIL/EPIC. The power of even rudimentary ENA measurements for probing the global ring current is thus well established. With the launch of POLAR we are obtaining a data set that provides routine global measurements of ENAs. Owing to POLAR/CEPPAD's high sensitivity to ENAs, we can use these data to explore the ENA/*Dst* relationship not only during all phases of moderate geomagnetic storms, but also during quiescent ring current periods.

INTRODUCTION

Energetic Neutral Atom (ENA) measurements have been reported since the 1970's. Hovestadt and Scholer

Paper number .

[1976] first suggested that highly anisotropic energetic hydrogen measurements were observations of energetic neutrals generated by the charge exchange of ring current particles with the tenuous hydrogen geocorona. The first association of ENA flux with ring current activity was done by Roelof et al. [1985]. They showed ENA measurements from IMP 7/8 and ISEE 1, and demonstrated, using hourly averages, a rough correspondence between ENA count rate and the *Dst* index.

Recently, Lui et al [1996] have reported on the first direct composition measurements of ENAs. They reported data from a single GEOTAIL pass around the dayside of the earth, in which the ring current ENA flux was observed continuously for about 12 hours.

We demonstrate further value of ENA measurements using data from the POLAR/CEPPAD Imaging Proton Spectrometer (IPS) [Blake et al., 1995]. The first ENA images from POLAR/CEPPAD have previously been repoted by Henderson et al. [1997]. In contrast to previous ENA measurements, our observations suggest a relationship between ENA production and the *Dst* index, rather than the time derivative of the *Dst* index.

DATA SET AND ANALYSIS

Although designed primarily to measure energetic ions, the IPS has the ability to detect energetic neutrals. Energetic neutrals are identified as a weak signal of highly directional particles coming from the general direction of the earth (see for example figure 2a in Henderson et al. [1997]) In this paper we use data from the energy integral channel, which samples the complete unit sphere in 256 "pixels": 9 look directions from parallel to anti-parallel to the spacecraft spin axis and; 32 sampling intervals (sectors) in each spacecraft spin (except for the spin-aligned look directions, which sample 16 times per spin) This channel integrates over the full energy range of the IPS (15 keV-1500 keV) every 6 second spin. These data cover the full range of energies responsible for the bulk of the ring current and plasma pressure in the inner magnetosphere.

From the full resolution 6 second data, 20 minute averages are produced at 10 minute intervals. In regions where there are no (or only very few) energetic ions, the signal observed by IPS has two components: The ENA flux from the magnetosphere; and an isotropic cosmic ray background. IPS is also sensitive to light, and consequently some pixels are contaminated by earthlight or sunlight. The first step in the reduction is to identify these pixels, and exclude them from our analysis. The next step in the reduction is to subtract out the background due to cosmic rays and small fluxes of energetic ions. A very simple method which has proved adequate in most cases is to assume that the background is isotropic. This is a very good assumption for cosmic rays, and even works well for subtracting out occasional weak Polar Energetic Particle (PEP) [Spence, et al., 1997a, Spence et al., 1997b] signatures. Then the background can be computed as the average count rate in the pixels that look away from the Solar magnetospheric (SM) equatorial (XY). When POLAR is at large distance from the earth, presumeably all ENAs are emitted relatively near the XY SM plane, and therefore pixels that look away from the XY SM plane observe only the background. This computed background is then subtracted from each of the pixels looking towards the XY SM plane. The result of these computations leaves us with a data set of "pure" ENA counts measured by the pixels looking towards the XY SM plane. Since a typical ENA count rate in a pixel is 1-5 cts/sec or greater, and a typical cosmic background count rate is 0.8 cts/sec, the 20 minute data set has typical counting uncertainties of 1.5-5%.

We introduce a measure that we call the Global Energetic Neutral Index (GENI). GENI is the total number of ENAs counted per second by the IPS instrument if it were at a certain normalization location taken to be 9 Re above the northern magnetic pole. The total includes the sum of cts/sec over all pixels that look towards the XY SM plane. Since the ENA source has a finite extent, the sum of cts/sec over all pixels will in general depend on the location of the satellite. In order to remove any biases due to the satellite location, we introduced the normalization location, transform the total counts measured at the satellites actual location to the total counts that would be measured at the normalization location. To do so, We assume that the ENAs measured by a particular pixel looking towards the XY SM plane are emitted isotropically from a point source located at the center of the projection of the pixel on the SM plane. We then compute the total ENA count rate as the sum of the emissions from a large number of point sources located throughout the magnetosphere as the weighted sum of each of these point sources. The weights are the inverse square distance from the computation point to the point source, and therefore the total ENA count rate at the standard point can be calculated as the weighted sum of the ENA count rate actually measured. The weights are the ratio of distance squared from actual location to center of projection on XY SM plane, to distance squared from standard point to center of projection on XY SM. Figure 1 illustrates this process graphically, and mathematically it is expressed as

$$n_{GENI} = \sum_i n_i \left(\frac{|\vec{r}_{sat} - \vec{r}_{prj,i}|}{|\vec{r}_{norm} - \vec{r}_{prj,i}|} \right)^2, \qquad (1)$$

where n_{GENI} is the Global Energetic Neutral Index, the sum is over all pixels that look onto the XY-SM plane, n_i is the ENA count rate in each pixel, $\vec{r}_{sat}$ is the location of the satellite, $\vec{r}_{prj}$ is the location of the center of the projected pixels, $\vec{r}_{norm}$ is the location of the normalization point.

Because most of the ENAs are emitted from the ring current region, we should expect a direct relationship between GENI and *Dst*. Indeed we find that the integrated ENAs track the provisional *Dst* index produced by the World Data Center C2 in Kyoto, remarkably well, as shown in Figure 2. The fact that the numerical values of the GENI and *Dst* indices are identical is purely a coincidence. It is important to note in figure 2 that GENI tracks *Dst* not only during the recovery phase of moderate storms (Days 10-18) but also during storm main phase (Day 28) and during prolonged quiet periods (Days 35-40).

DISCUSSION

There are several assumptions that we have made in producing the total ENA count rate. First, we assume that all ENA production takes place in the XY SM plane at a point which is the center of the projection of the corresponding pixel in IPS. This is obviously not true, since ENAs are produced wherever there are both neutrals and energetic ions - a region that extends quite far out of the XY plane. However when POLAR is at a sufficiently high altitude (for example Zsm $>$ 3 Re) this is probably a reasonable zeroth-order assumption. The other assumption we make is that from every point where ENAs are produced, they are emitted isotropically. This is obviously not true either, since the charge-exchange process that produces ENAs preserves pitch-angle information, and thus the ENA flux observed along a line of sight from a given location depends not only on the production rate at that location, but also on the pitch-angle anisotropy, and the angle between the magnetic field line and the line of sight. The reason that the assumption of isotropy is probably more reasonable than stated above is that each pixel of IPS is integrating over a large volume of space with a great variety of anisotropies, and field orientations in most cases, and therefore tends to diminish the importance of any local anisotropies.

The assocation between ENAs and the *Dst* has previously been discussed theoretically by Roleof et al. [1985]. They derived a relationship between the recovery rate of the ring current as measured by *Dst*, and the total ENA production in the magnetosphere. Using this relation they concluded that charge exchange dominates the ring current recovery. They only applied their relation to the storm recovery phase at times when the charge exchange process is thought to dominate the ring current loss and thus the recovery rate of Dst ($\frac{dDst}{dt}$. With POLAR we observe a proportionality between ENA production and the Dst index even during periods when the ring current is growing (i.e. storm main phase). Such periods were not considered directly by Roelof et al. [1985] so we explore along parallel arguments why ENAs should track Dst at all times.

The Dessler-Parker-Sckopke relation can be rewritten

$$\frac{\Delta B}{B_0} = \frac{< E > N}{E_B}, \tag{2}$$

where N is the total number of energetic ions in the ring current, and $< E >$ is their average energy. The total ENA production rate can be written as follows:

$$N_{ENA} = \int d^3r \int dE \int d\Omega j_{ion}(\vec{r}, E, \Omega, t)\sigma(E) n_H(\vec{r}), \tag{3}$$

which by use of the mean value theorem can be reduced to

$$N_{ENA} = \sigma(E_0) n_H(\vec{r_0}) N, \tag{4}$$

where E_0 and $\vec{r_0}$ are a "characteristic" energy and radius for the ring current respectively. Assuming that ΔB is a good approximation for Dst, we can combine (4) with (2) to obtain

$$N_{ENA} = \frac{E_B}{B_0}\left[\frac{\sigma(E_0) n_H(\vec{r_0})}{< E >}\right] Dst \tag{5}$$

Since our measurements indicate that $Dst = KN_{ENA}$, where K is a constant, the bracketed term in (5) must be constant. This most likely implies that E_0, $< E >$ and $\vec{r_0}$ are constant and independent of Dst for the storms we have observed, since both σ and n_H are rapidly varying functions of their parameters.

By careful inspection of ENA and Dst data values, we find that occasionally there is a tendency for measured ENA values to overshoot during main phase (i.e. too much ENA is produced to maintain a proportionality with Dst), and occasionally there is a tendency for ENA values to undershoot during recovery phase. This would be consistent with the inward motion of the ring current during storm main phase. As of yet these measurements are inconclusive, but they do yield the possibility of independently deriving the motion and energization of the ring current from measurements of the Global Energetic Netural Index. In addition, the energy of the ring current ions can be measured through

ENAs, fixing two of the three unknown variables, thus allowing us to determine the variation of $\vec{r}_0$ from small variations in the scaling factor between Dst and N_{ENA}

Our discussion of the direct relation between N_{ENA} and Dst actually does not contradict the results of Roelof et al [1985]. During storm recovery, the exponential decay of Dst with time means that $\frac{dDst}{dt} \propto Dst$. Thus we should expect Dst to be proportional to both Dst (our finding) and its derivative [Roelof et al., 1985]. During main phase, when the ring current is being formed, the general equation from Roelof et al. (1985) must be used. Their equation 10 includes the ring current source term which can be neglected during recovery phase (conclusion of their paper) but during main phase (solutins not considered in their paper). We show that this source term must be sufficiently larger than the loss term (ENA production) to grow the ring current at a rate such that Dst tracks ENA production. So in principle equation 10 or Roelof et al. (1985) can be used to measure the ring current energy injection rate given the derivative of the Dst index and the ENA production rate.

CONCLUSION

We have created a Global Energetic Neutral Index (GENI), which reproduces with surprising accuracy the Dst index. We feel that this index is an excellent proxy for the Dst index not only during storm recovery, but also during all levels of moderate geomagnetic activity. Smaller variations in the scaling factor between Dst and GENI may be used to explore details of the ring current evolution, such as the average energy of ring current particles, and radial location of the ring current. This study amply demonstrates the power of ENAs for probing quantitatively details of the global magnetosphere.

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Figure 1. GENI is calculated by re-normalizing the ENA counts to some standard location. This is done by first projecting the pixel count rates to the equator, and then recalculating the expected count rate at the standard position, from the projected points

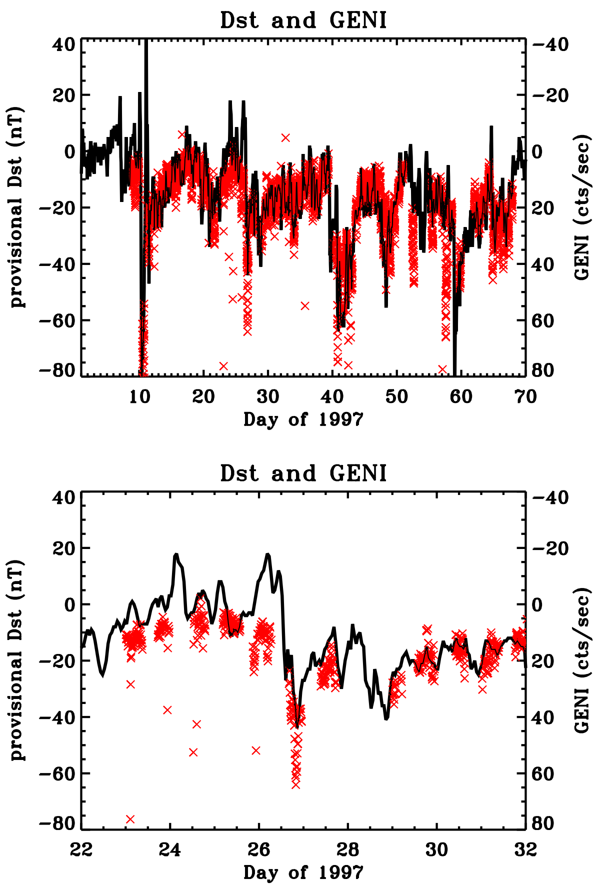

Figure 2. Dst and ENA as a function of time for the first 2.5 months of 1997, and a closer look at 10 days of data.